

Properties of the partially ionised flare chromosphere deduced from SDO/EVE Lyman Continuum observations

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Background:

The hydrogen *Lyman recombination continuum* emerges from the partially ionised solar chromosphere. It is enhanced during a flare due to increased ionisation. The Ly-C continuum is observed by the EVE instrument on SDO; here we report on measurements of its intensity and colour temperature, and their variation during a number of X-class flares.

The emergent intensity I_λ in the Ly continuum deviates from a blackbody. Using the Eddington-Barbier relation it can be written (Noyes & Kalkofen 1970):

$$I_\lambda \approx S_\lambda(T) \approx \frac{B_\lambda(T)}{b_1} \quad (1)$$

where S_λ is the source function at colour temperature T generated at optical depth $\tau_\lambda = \mu = \cos \theta$ (source position angle). b_1 is the level-1 departure coefficient. Since $T \sim 10,000\text{K}$, at UV frequencies, $B_\lambda(T)$ is calculated in the Wien approximation, $h\nu \gg kT$, giving:

$$I_\lambda(T) \approx \frac{2hc^2}{b_1 \lambda^5} e^{-hc/\lambda kT} \quad (2)$$

Assuming that b_1 does not change across the Ly-C emission region, the colour temperature T can be evaluated from the continuum slope.

Evaluating the Lyman continuum slope and colour temperature:

Two methods are used:

1) The **RANSAC** method (RANDOM Sample Consensus) fits an underlying trend in the presence of outliers (Fig 1) – e.g. EVE continua in the presence of emission lines (Milligan et al. 2014). We use it to determine a model continuum $I_\lambda = a_1 \lambda^{a_2}$

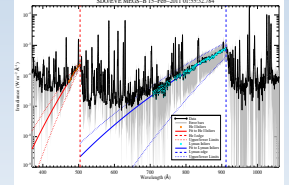


Fig. 1 Lyman and He I continua fitted using RANSAC (Milligan et al 2014)

2) Two well-separated spectral regions free of lines (predicted by Chianti) are identified and used in a direct evaluation of T_{col} from a ratio of Equation (2). The regions chosen are at 89.0nm and 73.5nm (Fig. 2).

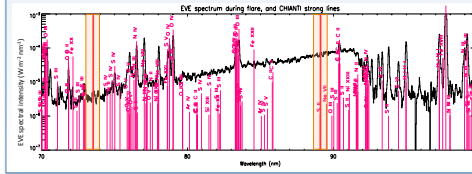
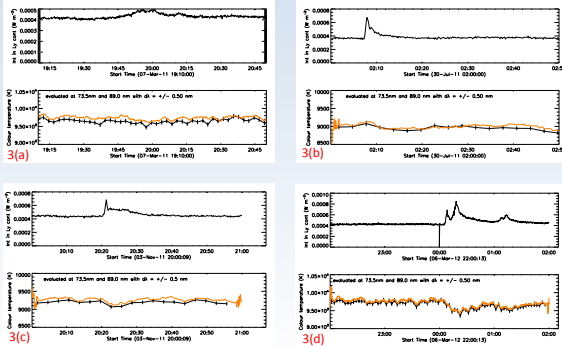


Fig 2 : the EVE Lyman continuum with lines from Chianti superposed (Dere et al 1997, Landi et al 2013). Orange-shaded regions reasonably free of strong lines are used in our calculation of colour temperature.

Evolution of the average Ly-C colour temperature - Sun-as-a-Star:

The average solar Ly-C and T_c during 4 X-flares are shown in Figs 3a-d. *Upper panels:* Ly-C intensity at 90.5nm. *Lower panels:* Ly-C T_c calculated with RANSAC fitting (orange) and intensity ratios (black).

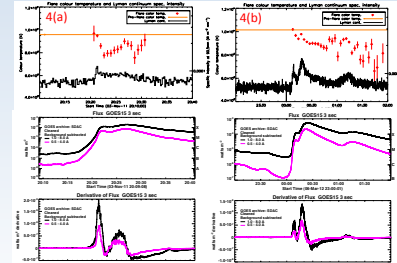
Flare-associated T_c decreases are small, but consistent between methods



Evolution of the flare colour temperature

The pre-flare spectrum is subtracted from the flare spectrum to give the flare excess spectrum.

The ratio method is used to evaluate the colour temperature of the flare excess, for the two flares showing strongest Sun-as-a-star variations, i.e. SOL2011-11-03T20:00 and SOL2012-03-07T00:10 (Figs 4(a) and (b))



Red = Ly-C colour temperature and its random error.
Orange = pre-flare colour temperature.

Significant decreases in the Ly-C colour temperature of up to 2000K are detected.

Colour temperature is depressed for some minutes after impulsive phase (see GOES derivative curves), as Ly-C slowly returns to pre-flare level

Departure coefficient – 2011-Nov-03:

From Figure 4(a) and (b) we see that $T = 8000\text{K}$ during most of the flare. Then the Planck function calculated in the Wien approximation at 90nm is

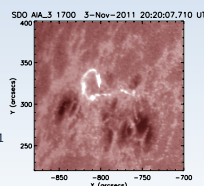
$$B_\lambda(T) \approx 42 \text{ W m}^{-2} \text{ nm}^{-1} \text{ sr}^{-1}$$

Using the 1700 Å AIA ribbons as a proxy for the Ly-C emitting area gives $A_f = 3.5 \times 10^{14} \text{ m}^2$.

The spectral power is $\pi B_\lambda(T) A_f = 4.6 \times 10^{16} \text{ W nm}^{-1}$.

In the 03-Nov-2011 flare the excess spectral irradiance at 90 nm at 20:22 UT is $7 \times 10^{-6} \text{ W m}^{-2} \text{ nm}^{-1}$ at EVE, or $2 \times 10^{18} \text{ W nm}^{-1}$ at the flare.

From Eq. (1), the departure coefficient $b_1 = 0.025$ which would mean H level 1 is overpopulated compared to LTE – unphysical. The Ly-C colour temperature or emitting area might be underestimated.



Summary and Interpretation

We examine the Lyman continuum (Ly-C) in a number of large flares observed by MEGS-B, charting the evolution with time of the colour temperature.

The Ly-C colour temperature decreases significantly during the flare impulsive phase, consistent with past observations (e.g. Lemaire et al 1984). However, the temperature is depressed for longer than the period of impulsive heating.

A decrease in the colour temperature indicates that the emergent intensity originates from cooler layers than in the quiet Sun. This is consistent with the overlying layers of the flare chromosphere becoming optically thin as they ionise due to flare heating, so that Ly-C from deeper layers is seen.

Preliminary calculations indicate an unphysical value of the level-1 departure coefficient, suggesting an *underestimate* of T_{col} or the Ly-C area.